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Fort Riley Earth Penetration Program – Davis Gun Test Results and Analysis (U)

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Abstract

The test phase of the DNA program became a joint program with Sandia National Laboratories (SNL). Four Davis Gun, earth-penetrator tests were conducted by personnel from Tonopah Test Range. Two tests were conducted using the SNL Albuquerque/Los Alamos National Laboratory cylindrical/flared penetrator design, and the other two tests were of the SNL Livermore/Lawrence Livermore National Laboratory tapered penetrator design. This report presents the test results and analysis of the data.

Acknowledgments

The earth penetrator portion of the overall effort was a joint Department of Energy/ Department of Defense (DOE/DOD) program. The DOD portion of the effort was conducted for the US Army Engineer Waterways Experiment Station (WES) by Sandia National Laboratories under MIPR number A35200-5-0011, dated March 8, 1985, under sponsorship of the Defense Nuclear Agency (DNA) as a part of Task Code RSRB, Work Unit 00037, "Earth Penetrator Research." The work was technically monitored by Dr. Behzad Rohani of the Geomechanics Division, Structures Laboratory, WES.

The SNLA penetrators were provided by Phase 1 and Phase 2 Division and the Penetrator Weapon Development Division, with support from the Telemetry Technology Development Division. The SNLL penetrators were provided by the Advanced Systems Division, with support from the Test Projects Division, and the Flight Test Instrumentation Systems Division.

Sandia's Tonopah Test Range was responsible for conducting the tests. This program was out of the ordinary for TTR personnel in that it was off-range; they did an outstanding job under difficult circumstances.

The Fort Riley Military Reservation is a training base, so supporting an R&D test operation was not routine. However, range support, and in particular the office of the Range Controller, was excellent, and we are grateful for their assistance.

Finally, the work by John Eichelberger (SNLA) and Glen Rawson (R&D Associates) on the site selection program was a necessary ingredient of the Davis Gun test program. Their effort is greatly appreciated.

Summary

A program was initiated by DNA to select a target of strategic interest, select a site in the CONUS as a suitable analog, and conduct penetration tests using [redacted]

The field test program was a joint DOE/DOD effort. The DOE had ongoing programs at both SNLA/LANL and SNLL/LLNL. In fact, both penetrator designs had undergone extensive testing in soil and soft, uniform rocks. The DOE therefore provided four instrumented penetrators for the program, and the DOD funded the field test effort. The DOD support came from the DNA, through the US Army Engineers Waterways Experiment Station, for SNL to perform the testing.

The field tests were conducted at Fort Riley in January 1986. The SNLL penetrator design utilized a tapered body for soil stability. Two 0.75-scale penetrator tests were conducted, with good penetration performance on both tests. There was slight structural damage to both penetrators, but in SNLL's opinion the damage would probably not have affected a weaponized EPW. No penetration data were obtained for these tests. The SNLA penetrator design (3 CRH ogive/cylindrical afterbody) utilize a flare to enhance stability. One 0.75-scale test and one full-scale test were conducted. Penetration performance was comparable to the SNLL design; there was no structural [redacted]

One objective of the tests was to evaluate the existing analytical techniques. The SNLA predictions covered axial motion and loads only, and on all four tests, the predicted depths were 10% to 14% low. On the two tests where deceleration data were recorded, the pretest predictions were close to the measured decelerations.

DOE b(3)

Nomenclature

CONUS	Continental United States
DNA	Defense Nuclear Agency
DOD	Department of Defense
DOE	Department of Energy
EPW	earth penetrating weapon
HTEPW	hard target earth penetrating weapon
LANL	Los Alamos National Laboratory
L/D	length to diameter ratio
LLNL	Lawrence Livermore National Laboratory
SEP	strategic earth penetrator
SEPW	strategic earth penetrating weapon
SNL	Sandia National Laboratories
SNLA	Sandia National Laboratories, Albuquerque
SNLL	Sandia National Laboratories, Livermore
TTR	Tonopah Test Range
USGS	United States Geological Survey
W/A	weight-to-area ratio
WES	US Army Engineers Waterways Experiment Station

- The relative importance of lateral or bending loads during penetration of nonuniform hard targets is now better understood, and short penetrators are more desirable from this standpoint.
- Advances in the design of rugged nuclear EPWs, which no longer require sharp noses and high W/As, make the earth-penetrating (EP) case designs more compatible with the nuclear system designs.

Until recently, penetrator configurations were selected to meet two criterion. First, they had to be terradynamically stable in soil to prevent broaching. This was accomplished with the flare and taper designs as shown in Figure 1. Second, they had to survive the penetration of rock without rebounding. For the latter criterion, targets of exposed uniform rock were selected for testing. [redacted]

In 1984, Behzad (Bob) Rohani, WES, and the author met with members of the Geological Survey (Jack Rachlin, Bill Dempsey, and Selma Bonham) to estimate the penetrability of [redacted]

[redacted] This revelation opened up the number of targets that could potentially be defeated by the moderately hard penetrator designs.

The Defense Nuclear Agency (DNA) was already in the process of reevaluating the applicability of nuclear EPWs. The program that evolved served both to evaluate existing EPW technology and to extend that technology into the area of weathered rock. First, a site selection program, briefly summarized below, was conducted.[1] A field test program, which is the subject of this report, was conducted as the second part of the effort.

Both SNLA and SNLL have ongoing Phase I/II programs (weapon concept through proving feasibility) to develop a strategic EPW. The parallel programs have both resulted in penetrator designs with proven structural and penetration performance. Since the field test portion of the DNA program was of mutual interest to the DOE and the DOD, it became a joint program.

Site Selection Program

This section briefly summarizes the results of the site selection program; this summary is limited to the points most relevant to the penetration program. Reference 1 contains complete documentation of the effort.

The primary consideration was that the site selected be geologically representative of the environment of interest,[1] but practical constraints related to the penetrator test and recovery operations also had to be considered. The target area had to be at least a mile from inhabited areas, preferably on a military installation, with clear air space above the test site, and had to be accessible by the mobile Davis Gun, which weighs ~40 tons. Finally, recovery operations would be much easier if the soil overburden was less than about 5 ft and if the water table was below the expected penetration depth.

The selected site was on the Fort Riley Military Reservation in Kansas. Figure 2 shows a road cut a few miles from the site, where the geology is similar to the test area. The selected area was cored so that the rock could be characterized. The coring was done by the US Army Waterways Experiment Station (WES). Their pretest coring results are included in this report as Appendix A to aid in interpreting the penetration data. A more comprehensive coring and material property testing was conducted by WES after the EPW tests were completed.[3] The final site selection was verbally approved by representatives from R&D Associates, WES, USGS, DOE, and DNA.

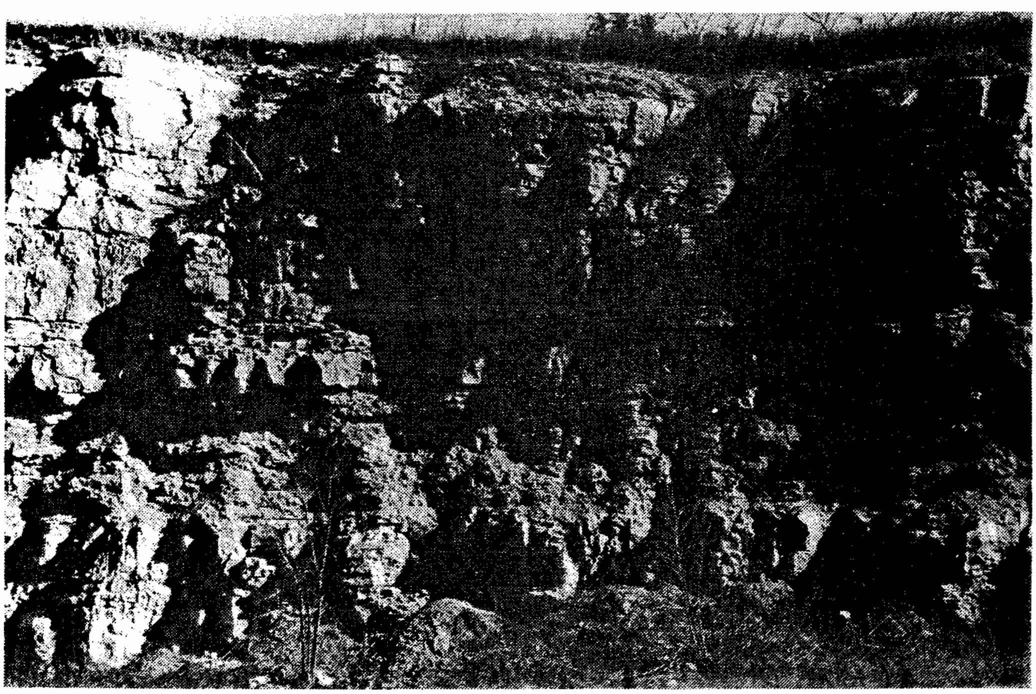

Figure 2. Road Cut at Fort Riley

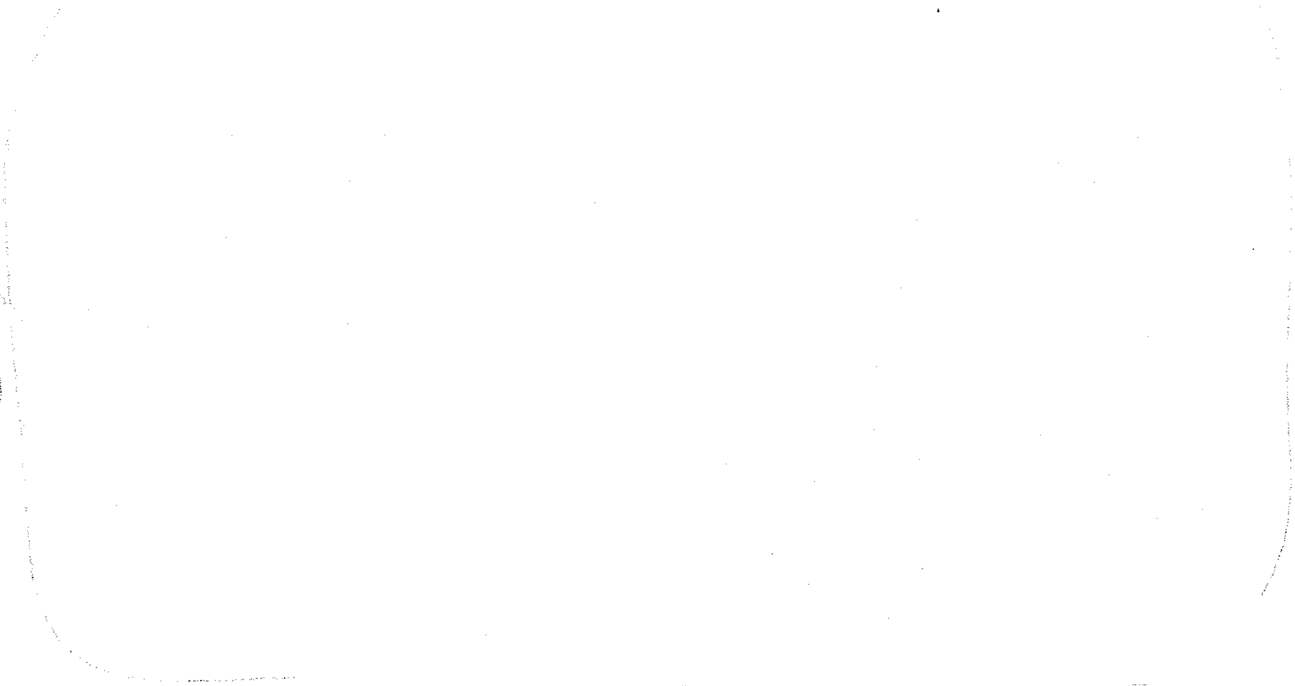

Figure 5. Strategic Earth Penetrator, SEPW-DG3

Test Facility

The mobile Davis Gun test facility was used for the penetration tests at Fort Riley. This facility is operated by personnel from the Tonopah Test Range (TTR), near Tonopah, Nevada. Penetrator recovery operations were performed by personnel from Reynolds Electric Co., under contract to TTR.

The Davis Gun is a recoilless gun system that fires projectiles in opposite directions. One projectile is the penetrator, and the other is a reaction mass. Figure 6 shows an artist's concept of the gun. The gun trailer weighs ~68,000 lb, including 20,000 lb for the gun barrel. The trailer contains hydraulics to raise the gun to any desired angle, to pull the projectile assembly up into the gun barrel, and to set the outriggers to provide lateral stability and leveling. A separate electric generator is required to power the facility. The gun barrel is 35 ft long, 12 in. ID, 19 in. OD, and has a working pressure of 50,000 psi. The maximum launch conditions are usually limited by the structural capability of the penetrator. The Davis Gun has been used to fire a 150-lb penetrator at 3200 ft/s and a 720-lb penetrator at 1700 ft/s.

There are several ways to control the penetrator velocity, while at the same time limiting the launch pressure and acceleration. An explosive propellant is used to launch the penetrator and reaction mass from the gun. Both the chemical and physical properties of the propellant control the burn rate. Even after selecting the propellant type (M30 is usually used), the web size of the grains can also be varied to control burn rate. The total propellant weight and the initial volume of the burn chamber are independently varied. A low-energy detonator is used to ignite black powder (about 1 lb per 50 lb of propellant), which in turn ignites the propellant. The weight of the reaction mass relative to the penetrator assembly can be varied for additional control of launch conditions (a ratio of ~4 to 1 is optimum). Finally, the whole assembly can be positioned in the gun barrel to limit the velocity. In practice, the assembly is usually positioned so that the penetrator and reaction mass exit the barrel at the same time.

The angle of attack is obtained by designing the pusher plate and foam sabot to hold the penetrator at the desired angle as it is fired from the gun.

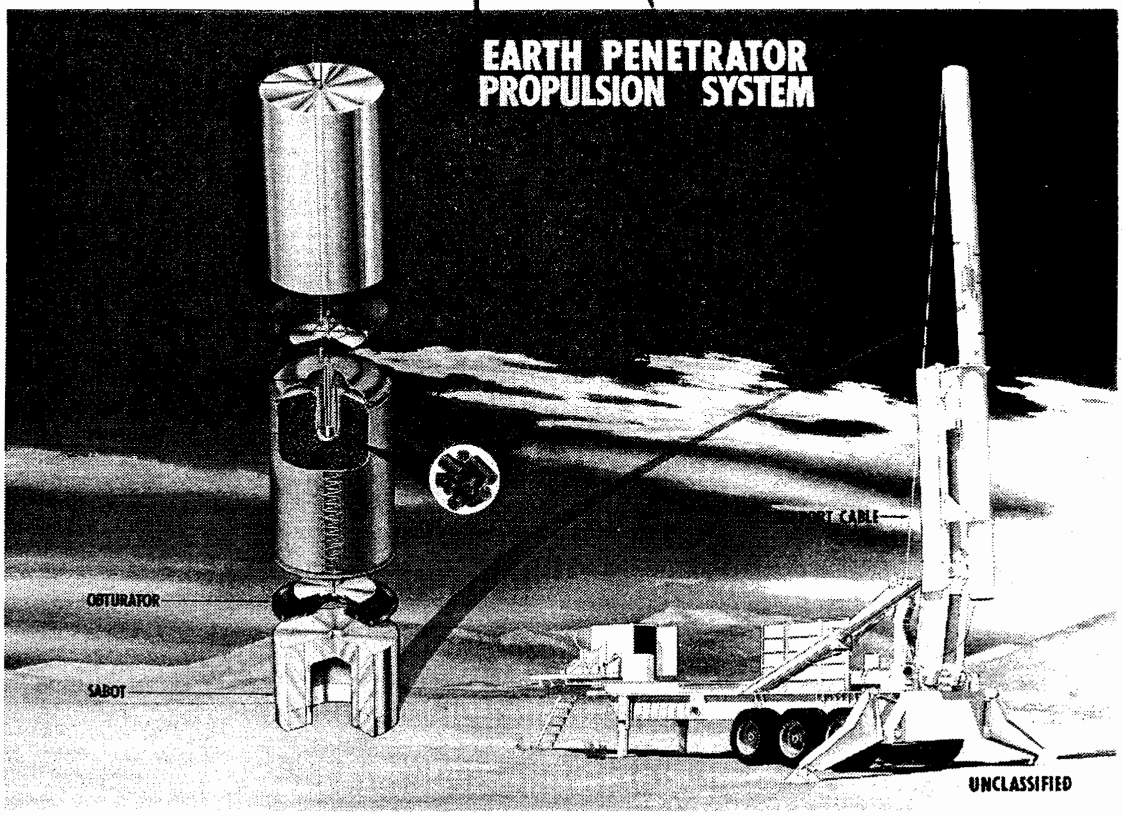

Figure 6. Davis Gun, Artist's Concept

Camera coverage of the Fort Riley tests consisted of:

- Two image motion (Hytax) cameras, side view
- Two Fastax II (3000 frames per second, fps) movie cameras
- One overall movie, at 400 fps
- One hand-held, 16-mm movie to document events related to test setup and recovery operations.

One additional instrumentation van, located a safe distance from the gun site, was required to operate the facility. This multipurpose van, operated by the Telemetry Technology Development Division of SNLA, was used as a firing trailer for the gun. Its primary purpose was to support the instrumentation packages in the penetrators, and both SNLL and SNLA provided personnel for this effort. Pressure in the gun barrel during launch was also measured and recorded in the van.

Test Conditions

The test plan is given in Table 1. All four tests were conducted in one target area. The first two tests were planned to compare the flared and tapered penetrator designs under similar impact conditions. The second and third tests were planned to compare the 0.75-scale to the full-scale penetrators. Since the SEPW-DG3 penetrator is 12 in. in diameter at the aft end, it was not possible to fire it at an angle of attack. Also, a lower impact velocity and larger impact angle were selected so that both penetrators would traverse approximately the same rock profile. The original plan was to have the last test at a lower impact angle to compare with the first two tests, but before test time, it was decided to test at a near-vertical angle.

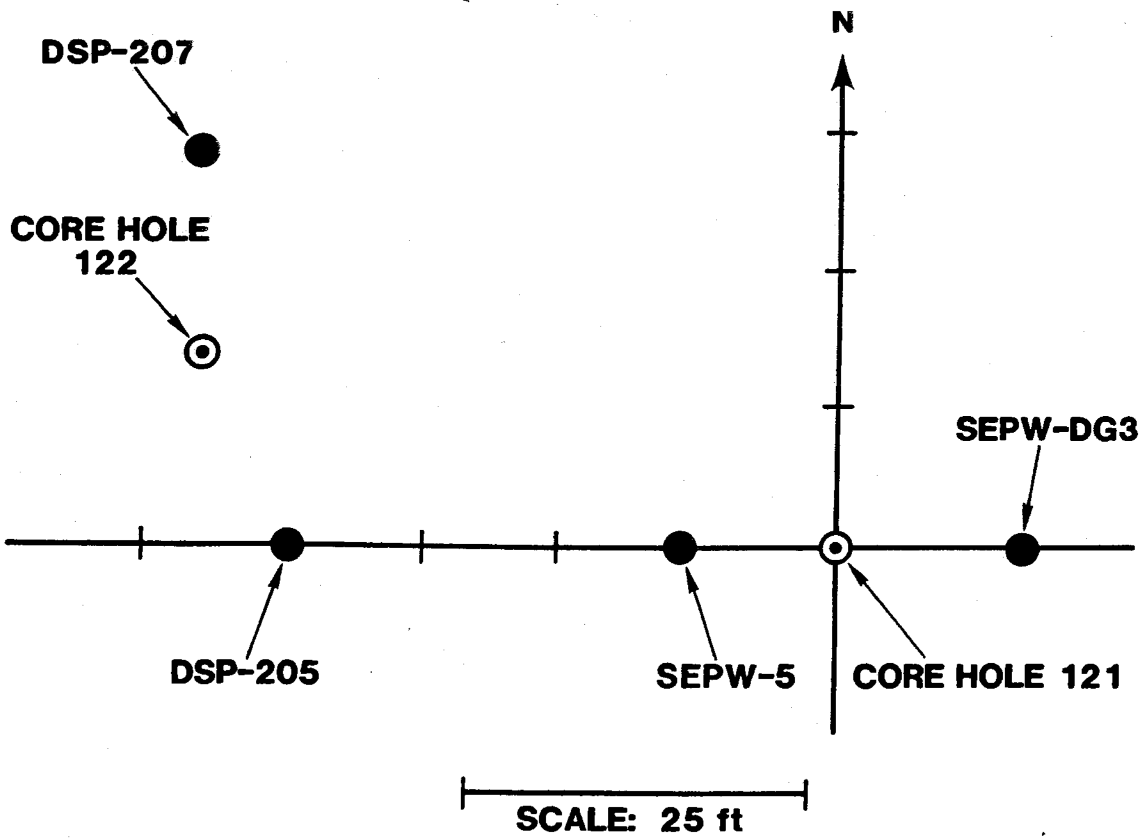

Figure 12. Plan View of Impact Sites

Test SEPW-DG3

Figure 19 shows the impact point for this test. The surface heave was very pronounced, but this was to be expected for this full-scale penetrator. Figure 20 shows the trajectory, and Figure 21 shows the recovered penetrator. There was no penetrator damage, and acceleration data were obtained. Because this penetrator was too large to manhandle, it had to be almost completely exposed with the jackhammer before it could be recovered. It was observed during recovery greater than its rest position. During essentially all penetration tests, the rebound phenomenon occurs, but with no relative motion between the penetrator and soil or rock.[4] At this time, there is no way to determine whether a physical gap ahead of the penetrator occurred during the other three tests at Fort Riley. This subject will be readdressed later in this report in the discussion on acceleration data.

Figure 19. Impact, Test SEPW-DG3

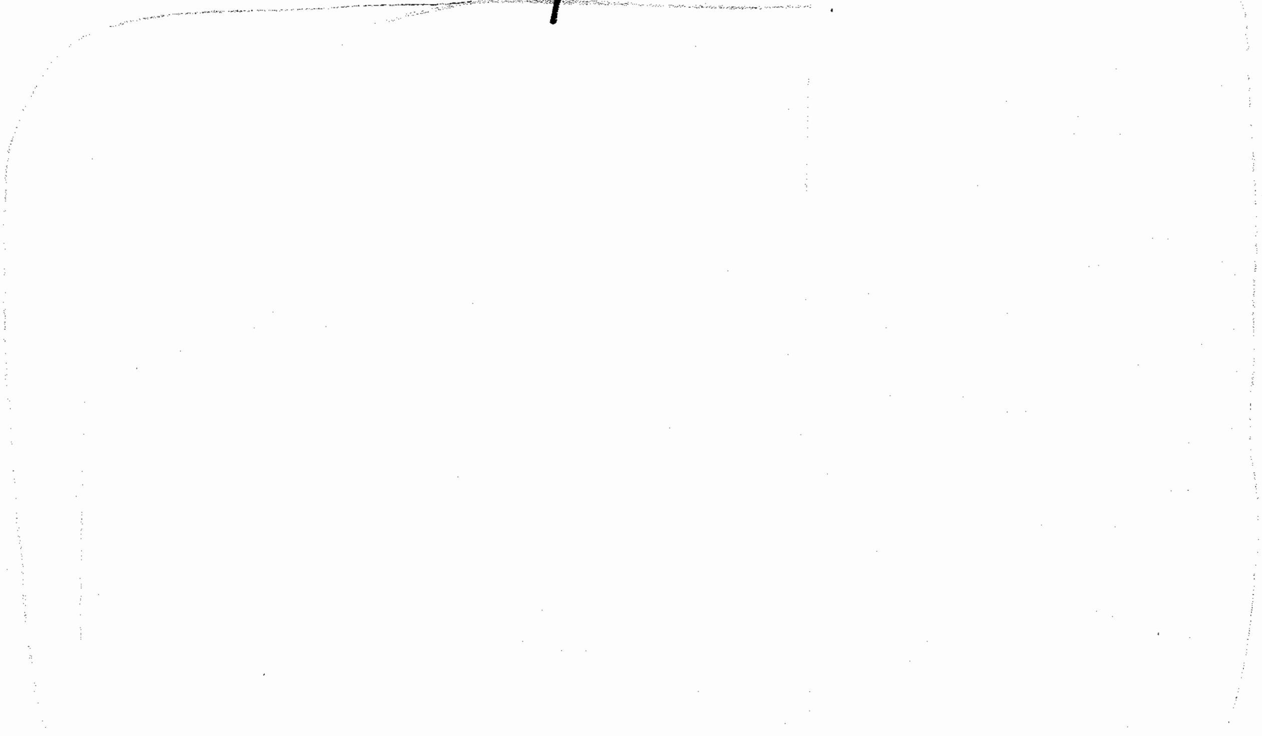

Figure 25. DSP-207, Recovered Penetrator

Data Reduction

Since the instrumentation packages failed during tests DSP-205 and -207, the only data obtained were launch conditions and penetration performance, discussed elsewhere in this report. This section examines data as recorded in the penetrator during tests SEPW-5 and SEPW-DG3.

SEPW-DG5

Appendix B contains the data reduction report for this test. The instrumentation package records and stores the data during launch and penetration, then holds the data in active memory until the penetrator is recovered. Reference 5 contains a detailed description of the system. Also, a brief description of the data system is included in the data reduction report.

The barrel pressure was recorded directly from a pressure gage in the gun barrel and is independent of the instrumentation package in the penetrator. The pressure is recorded to show that the internal ballistics of the gun is correct.

The next sheet in the report shows the acceleration record in the gun barrel, followed by ~5 ms of free flight, and then axial deceleration during penetration. The impact time was selected manually after viewing the data and could be as much as 1 ms in error.

Note that on the acceleration-time records ~20 ms after impact, the acceleration becomes positive and remains positive for ~12 ms. The sign convention used is that the direction of the impact velocity is positive; therefore, the force resisting penetration is a negative force. A positive force is then either a force pushing the penetrator into the target or a force resisting a penetrator that is traveling out of the target (rebounding). The acceleration-time record and its two integrals show:

DOE b(3)

[redacted]

SEPW-DG3

Appendix C gives the data for this test. Most of the comments related to the SEPW-5 data apply to this test. The rebound phenomenon was essentially the same on this test, except that it was observed during recovery that the actual penetration hole was ~8 in. beyond the penetrator nose. Although it has been suggested that the rebound in the acceleration record is either an electrical or mechanical (within the penetrator) "overshoot," the frequency response of the accelerometer and its mounting virtually eliminate these as possibilities.

Comparison With Predictions

One of the objectives of the field test program was to compare the pretest predictions with measured results to evaluate the predictive tools. References 6 and 7 contain details of the predictions published by the WES. The SNLA pretest predictions are given in Appendix D and are further discussed below.

This program was very illuminating regarding the validity of data on which penetration performance predictions are based. In Reference 1, John Eichelberger addressed the subject in geologic terminology. He said, in layman terms:

[redacted]

- Examination of the core samples led several analysts to expect the target to be rather strong. Of course, this was because adequate cores could be recovered only from the more competent rock.
- After the core samples had been tested in the laboratory, the report in Appendix A was published. Again, the tendency was to overestimate the target strength (in terms of penetrability), from the core sample data.
- Finally, during recovery of the penetrators, the impression was that the target was very soft, or essentially a clay-like material. In fact, the ground water tended to wash the clay out of the weathered rock onto the wall of the recovery trench, at times obscuring the actual rock structure.

The point of the above discussion is that in actuality any one of the above target descriptions could be the only one available. It is quite possible that errors in our predictive tools may be insignificant in comparison to various interpretations of target descriptions.

To make the predictions used in Appendix D, the information shown in Figure 26 was used, supplemented by observations of the cores and the road cut. The right-hand column in Figure 26 describes the penetrability of the various layers in terms of S-numbers. The predictions were of penetration path length and rigid-body deceleration. The empirical predictive technique is described in Reference 8, but the rock penetration equations of Reference 9 were used. The comparisons of predicted to measured penetration performance for each of the tests follow.

[redacted]

DOE b(3)

Conclusions

DOE b(3) & b(1)

[redacted]

3. It was shown that analytical techniques do exist to predict both penetration distance and the deceleration profile; and given the random and heterogenous nature of the targets, the predictions were reasonably close. No attempt was made by Sandia to predict the lateral loads.

[redacted]

DOE b(3)

APPENDIX A

WES Report

"Unconfined Compressive Strengths and Composition Properties for Rock Core From Fort Riley, KS"

UNCONFINED COMPRESSIVE STRENGTHS AND COMPOSITION PROPERTIES FOR ROCK CORE FROM FORT RILEY, KANSAS

by

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January 1986

Prepared for: Defense Nuclear Agency
Washington, DC 20305
Under Task Code RSRB, Work Unit 00037

UNCONFINED COMPRESSIVE STRENGTHS AND COMPOSITION PROPERTIES FOR ROCK CORE FROM FORT RILEY, KANSAS

CHAPTER 1

BACKGROUND

The U.S. Army Engineer Waterways Experiment Station (WES) was tasked by the Defense Nuclear Agency (DNA) to locate a geologic setting of military relevence within the United States for conducting projectile penetration experiments. Review of existing geologic data by a site selection working group (SSWG) identified Fort Riley, Kansas, as meeting the necessary criteria. Two test sites, referred to as Area I and Area II, were identified within the Fort Riley reservation. The U.S. Army Engineer Kansas City District (MRK) was tasked by WES to conduct initial drilling operations at these areas in order to develop subsurface profiles of the sites and to obtain rock core for unconfined compression and other engineering index testing.

The unconfined compression and index tests were conducted by WES. This report documents the results of those tests.

CHAPTER 2

TEST RESULTS

Two shipments of core obtained from boreholes numbered DC 85 121, DC 85 122, DC 85 124, and DC 85 125 were received by WES from MRK. Boreholes DC 85 121 and DC 85 122 are located in Area I. Boreholes DC 85 124 and DC 85 125 are located in Area II. The rock core from the first shipment was sealed in wax. The second shipment was received almost 1 month after the first, and the rock core was not sealed in wax. As a result, the rock appeared dried out. Tests later verified that the rock of the second shipment was not representative of in situ conditions and the results are therefore not included on any of the analyses plots. However, the test results are recorded in Table 1 for information purposes only.

After receiving the rock core, samples were prepared for testing. Each specimen measured approximately 2.15 inches in diameter and was prepared to approximately 4.5 inches in height. Actual height and diameter measurements were taken and the specimen was weighed. The wet density (γ) of the specimen was calculated as:

$$\gamma = \text{wet weight/volume}$$

The specimen was then placed in a Tinius-Olsen loading device (No. 35270) and statically tested in unconfined compression. Each specimen was loaded to failure or rupture and the load at rupture recorded. The compressive strength was calculated to be:

$$UC = \text{load at rupture/original cross-sectional area}$$

A portion of the sample was oven dried at 110° $\pm$ 5°c in order to obtain a water content, which was calculated as:

$$w = \text{weight of water/weight of solids}$$

The dry density (γ_d) was calculated by:

$$\gamma_d = \gamma/(1+w)$$

Table 1 gives a summary of the test results and compositional properties of these test specimens.

The first two columns in Table 1 record the number of the boring and the depth interval from which the specimen was taken. Column three gives a brief description of the core specimen, column four records the unconfined compressive strength of each specimen, and columns five through seven give the measured composition properties γ , w , and γ_d . The estimated grain density values in column nine were taken from The Handbook of Physical Constants*. The porosity (n) in column eight was calculated using the following equation:

$$n = \frac{G_s - \gamma_d}{G_s} (100)$$

where: G_s = grain density (gm/cm^3)

γ_d = dry density (gm/cm^3)

The results shown in Table 1 are graphically represented in Figures 1 through 4 for each boring. These figures show, for each boring, the variation with depth of material type, wet density, water content, unconfined compressive strength, and porosity.

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* The Geological Society of America, Inc.; Handbook of Physical Constants; 1966, The Geological Society of America, Inc., New York.

APPENDIX C

Data Reduction Report, SEPW-DG3

FEB 18 1986

TEST NO : SEPW–DG3 R804068

TEST DATE: January 11, 1986

TEST SITE: FT. RILEY, KS

Davis Gun Barrel Pressure, and
Earth Penetrator Acceleration Data

SEPW–DG3

Report Prepared By: W. R. Wood, 5144

Data Reduction By: [signature], 7522

Approved By: [signature], 7522

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7173 G. L. West
7522 F. D. Gutierrez

SEPW–DG3

Enclosed is the data obtained in support of a request to instrument and launch from the Davis Gun an earth penetrator.

DOE b(3) & b(1)

DOD b(3) b(1)

The acceleration vs. time data plots in this report are presented.

a) Exactly as they were stored in the data package memory during the penetration event.

b) Filtered during data reduction with to a 10 KHz digital low pass filter

c) Filtered during data reduction with a 5 KHz digital low-pass filter

d) Filtered during data reduction with a 1 KHz digital low-pass filter

W. R. Wood
W. R. Wood, 5144

SEPW-DG3

Data Package

A PCM Memory system with eight data inputs (BSS). All eight data inputs were used for one axial acceleration measurement (data frequency maximization).

Memory System Capacity: 49,152 bits

Bits Per Data Word: 6

Data Bit Rate: 244 K bits/sec

Memory Data Window Length: 201 ms

Data Sample Rate: 40,960 samples/sec

Data System Anti-Aliasing Filter 6 db Point: 10 KHz

System Data Resolution = 346 gs/cnt.

Accelerometer

Endevco 7270 Mounted Resonant Frequency = 700 KHz

The 7270 accelerometer was hard mounted to the data system battery package on this test.

Function	Data Channel Scale	Type	Serial No.
		Endevco 7270	AAA29F

Data System Filter

Anti-aliasing filter 6 db point (4 pole) = 10 KHz. This filter was a characterized low pass filter which processed accelerometer output data providing deconvolution capability if desired (frequency enhancement).

W. R. Wood
W. R. Wood, 5144

APPENDIX D

Letter, Young to Distribution: Prediction of Penetration Performance, Fort Riley Tests

~~SECRET~~ UNCLASSIFIED

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: November 13, 1985

to: Distribution

from: C.W. Young, 5340

subject: Prediction of Penetration Performance, Ft. Riley Tests

The purpose of this memo is twofold. First, TTR needs to know the expected penetration depth so they can better plan the recovery operations. Secondly, one of the objectives from the Defense Nuclear Agency's (DNA) viewpoint is to evaluate our calculational capability in a "real" target.

Determining what material properties to use in the analytical model can be a real problem when the target is weathered. Coring data is available, and several of us have viewed the core samples, so I suppose we are starting with adequate data. Two test areas are being considered, Area I being near the top of the hill, and Area II being about 200 feet downhill in a southerly direction. I used the following S-number profiles:

[redacted]

DOE b(3)

At this time, the SAMPLL code should not be used to predict lateral loads when the surface material is softer than the deeper layers. We do not have an analytical tool for calculating lateral loads for these tests, but my opinion is that the lateral loads will be equal to or greater than the axial loads. Also, only penetrator DSP 205 has lateral accelerometers. My predictions regarding penetration performance along the penetration path follows.

[redacted]

DOE b(3)

~~SECRET~~